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RESEARCH STUDY TO IDENTIFY TECHNOLOGY
REQUIREMENTS FOR ADVANCED EARTH-
ORBITAL TRANSPORTATION SYSTEMS,
DUAL-MODE PROPULSION

SUMMARY REPORT

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DUAL-MODE PROPULSION (Martin Marietta Corp.)
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NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

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**Research Study to Identify Technology Requirements
for Advanced Earth-Orbital Transportation Systems**

Summary Report

by

Martin Marietta Corporation, Denver Division

SUMMARY

This report summarizes the results of a study of dual-mode propulsion concepts applied to advanced earth-orbital transportation systems using reusable single-stage-to-orbit (SSTO) vehicle concepts. Both series-burn and parallel-burn modes of propulsion were analyzed for vertical takeoff, horizontal landing vehicles based on accelerated technology goals. A major study objective was to assess the merits of dual-mode main propulsion concepts compared to single-mode concepts for carrying payloads of Space Shuttle type to orbit.

INTRODUCTION

Studies have been under way during 1975 and 1976 to identify technology requirements for advanced earth-orbital transportation systems that will follow the present Space Shuttle program. These requirements were derived by focusing on goals to develop fully reusable single-stage-to-orbit (SSTO) vehicle concepts. Projections of technology that could be available in the 1985 to 1990 time period as a base for developing such SSTO vehicles were made under the assumptions of both "normal" and "accelerated" growth of technology.

This growth depends on the R&T (research and technology) activities during the next 5 to 10 years, which could achieve the desired goals through focusing on the future needs of SSTO vehicle designers and program operations. The relative cost and performance benefits of the various R&T activities can be assessed by use of such figures of merit as vehicle weight improvements and life-cycle cost reductions resulting from technology growth. Among high-yield areas of technology are materials, structures, and propulsion.

Previous technology assessments, reported in reference 1, were made using vehicle concepts with main propulsion engines burning liquid oxygen and liquid hydrogen propellants (i.e., single-mode engine concepts). Further assessments of the merits of dual-mode

propulsion concepts (i.e.,) burning high density fuels as well as liquid hydrogen) were desired to help determine the future direction of propulsion R&T activities.

The study results using dual-mode concepts are described in this report. Both parallel and series propulsion concepts are applied to vertical takeoff (VTO) vehicle designs. Vehicle weights and life-cycle costs are derived. Assessments of the merits of dual-mode propulsion are made relative to single-mode propulsion using figures of merit techniques. This study activity is a continuation of the study and results of reference 1, and the relative assessments and conclusions are consistent with and augment those of reference 1.

SYMBOLS

C^*	characteristic velocity
F_{vac}	engine vacuum thrust
F/W	thrust/weight ratio
FOM	figure of merit
GLOW	gross liftoff weight
g	acceleration of gravity
I_{sp}	specific impulse
LH_2	liquid hydrogen
LO_2	liquid oxygen
M	mach number
NPSH	net positive suction head
O/F	oxidizer-to-fuel mixture ratio
P_A	atmospheric pressure
P_C	thrust chamber pressure
RP-1	hydrocarbon fuel, type RP-1
RSI	reuseable surface insulation
SL	sea level
TPS	thermal protection system
VTO	vertical takeoff
W	weight
WBO	burnout weight
WP	ascent propellant weight
WPL	payload weight

W_L	landing weight
$\dot{W}$	propellant flow rate
α	angle of attack
ΔW_{DRY}	dry weight increment
$\Delta \$LCC$	undiscounted life-cycle cost increment
$\Delta \$LCC_D$	discounted life-cycle cost increment
$\Delta \$R$	undiscounted research cost increment
$\Delta \$R_D$	discounted research cost increment
ΔV_1	mode 1 velocity increment
ΔV^*	ideal total velocity increment
ϵ	nozzle expansion ratio

Subscripts:

1	mode 1
2	mode 2
c.g.	center of gravity
SL	sea level
T	total

TECHNOLOGY BASE

The research study reported in reference 1 identified technology areas that have a potential for cost and performance benefits with both "normal" and "accelerated" growth. The anticipated goals of the accelerated R&T activities in eight areas were shown to have significant potential payoffs. These areas, described in reference 1, were as follows:

- (1) Thermal protection system (TPS)
- (2) Propellant tanks;
- (3) Wing and fin structure;
- (4) Thrust structure;
- (5) Subcooled propellants;
- (6) Subsystem weights;
- (7) Miscellaneous structures;
- (8) Integration engineering (including launch and flight operations).

The goals for accelerated R&T activities in these areas, combined with goals for normal growth in other areas of technology, were used to derive vehicle concepts for vertical takeoff (VTO) and horizontal takeoff (HTO) modes (ref. 1). Single-mode propulsion concepts were used, that is, main engine propellants were liquid oxygen (LO_2) and liquid hydrogen (LH_2). The VTO vehicle concept developed under these guidelines that assumed advanced technology growth was used as a point of departure (a reference vehicle) for the present study to determine the possible additional advantages of dual-mode propulsion applications.

The single-mode VTO vehicle is illustrated in figure 1, whereas its materials and thermostructural features are identified in figure 2. This vehicle uses load-carrying, aluminum, integral-membrane tanks for carrying its LO_2 and LH_2 main propellants.

The hydrogen tanks are a multilobe design whereas the oxygen tanks are cylindrical. Reuseable surface insulation (RSI) is used to thermally protect the vehicle structures during ascent and entry flight. Seven main rocket engines are used, three of which have two positions so they can operate at high altitudes with a larger expansion ratio than at sea level. Some performance characteristics of these engines, considered to be of the SSME type with approved performance obtained by normal technology growth and product development, are as follows:

	Single-position	Two-position
Number per vehicle	3	4
Thrust, SL - 10^3 N (10^3 lbf)	2198 (494)	2198 (494)
Thrust, vacuum - 10^3 N (10^3 lbf)	2462 (553)	2554 (574)
I_{sp} , SL - sec	399.0	399.0
I_{sp} , vacuum - sec	445.2	466.3
Engine weight - kg (lbm)	1865 (4112)	3850 (8489)
Chamber pressure - 10^6 N/m ² (psia)	27.6 (4000)	27.6 (4000)
Expansion Ratio	55	55/200

The dual-mode engine characteristics used in this study are results of the parametric engine studies of reference 2. Applied to an SSTO vehicle, the parallel burn concept (figure 3) uses two types of engines at liftoff, one type burns LH_2 fuel and the second type burns a high-density fuel (RP-1 is used for the present study). During the flight, the RP-1 engines are shut down and one or more LH_2 engines continue to operate until orbit is achieved. The series-burn concept uses an RP-1 engine as well as a dual-fuel engine; the latter capable of burning RP-1 at liftoff, and switching to LH_2 fuel later in the flight.

A number of dual-mode engine parameters were examined for their effects on vehicle size, including engine cycle, thrust level, nozzle expansion and chamber pressure. Selections of the optimal values are presented later along with vehicle designs. Variations of engine thrust-to-weight ratios with thrust level are illustrated in figure 4 (based on results of ref. 2). Typical engine performance data are tabulated in table 1.

VEHICLE ANALYSIS AND DESIGN

Approach

The potential benefits of dual-mode propulsion compared to all LO_2/LH_2 single-mode propulsion were derived by examining variations of vehicle parameters and design concepts leading to optimal, minimum dry-weight vehicles, and program costs. Design iterations were made using design layouts to establish bases for vehicle sizing, thermostructural loads and mass properties, together with flight performance analyses to establish mass ratio requirements and engine utilization strategies. The ascent strategies for optimal performance included use of two-position nozzles, engine throttling to 60% full throttle, sequential time-phasing of mode 1 (RP-1) engine shutdowns, and gimballed nozzles on mode 2 (LH_2 and dual-fuel) engines. The relative amount of RP-1 fuel to be consumed was varied to determine the near-optimal propellant loading fractions for each vehicle design.

Guidelines for design such as orbit requirements acceleration limits and aerodynamic performance were the same as reported in reference 1. For example, ascent accelerations were limited to 3 g. The dual-mode vehicles also use the same thermostructural concept as for the baseline, extended performance VTO vehicle. Variations in internal arrangement of subsystems, however, were made to maintain good volumetric efficiency and minimum vehicle sizes.

Vehicle Design Parametrics

Variations of engine parameters were studied initially with a goal of achieving minimum vehicle weight. Of particular significance, the analyses showed the following features:

(1) Chamber pressures should be as high as practicable; the upper limits recommended in reference 2 were used, namely

LO_2/LH_2 engine: 27.6 m N/m^2 (4000 psia)

$\text{LO}_2/\text{RP-1}$ engine: 27.6 m N/m^2 (4000 psia)

Dual-fuel engine: 27.6 m N/m^2 (4000 psia) for RP-1 cycle and 20.7 m N/m^2 (3000 psia) for LH_2 cycle.

(2) Tradeoffs among ascent flight performance, specific impulse and nozzle weight lead to nozzle expansion ratios of 55 at sea level and 200 at altitude (similar results were shown in reference 3). Packaging and geometric features of two-position

nozzles optimally should be determined in conjunction with the vehicle design. Nozzles are extended as soon as possible when the ambient pressure during ascent becomes less than three times the nozzle exit pressure.

(3) For parallel burn, the RP-1 engine (and vehicle) is better using a gas generator cycle with LH_2 cooling than a staged combustion cycle. For series burn, the staged combustion cycle is desirable.

(4) Near-optimal designs result when the numbers of mode 1 engines and mode 2 engines are the same. Vehicles with only mode 1, dual-fuel engines are too heavy.

(5) For parallel burn, the LO_2/LH_2 engine should have thrust levels similar to SSME thrust levels to lower the engine DDT&E costs. For series burn, the RP-1 and dual-fuel engines should have the same sea level thrust for lower DDT&E costs.

Typical vehicle weight variations are shown in figure 5 as functions of the mode 1 velocity increment ratio. Data are shown for series and parallel burn vehicles, as well as for the reference single-mode vehicle (LH_2 fuel). Increasing values of ΔV_1 correspond to increasing amounts of RP-1 propellants consumed and used in the vehicle designs. The mass ratio requirements and tank volumes were, of course, varied as ΔV_1 was varied. The selected RP-1 propellant weight yields near-minimum dry weight. The LH_2 weight is plotted in figure 5 because this fuel costs 20 times more than LO_2 or RP-1. It was determined, however, that minimum program cost occurs for vehicles with near-minimum dry weight.

The results of vehicle resizing with variations of design features are summarized in figure 6. In addition to features previously discussed, these results indicate the following:

(1) Mode 1 engines with two-position nozzles lead to heavier vehicles than with single-position nozzles;

(2) Dry wing designs, with no RP-1 tanks in wing or wing box areas, are heavier than wet wing designs;

(3) Minimum vehicle dry weights are achieved using a large number (12) of main engines, as a result of the F/W data of figure 4. Cost considerations, however, lead to selecting designs with fewer engines;

(4) Liftoff accelerations of 1.29 g are better than 1.34 g.

Vehicle Designs

The dual-mode propulsion vehicle designs that result from the design iterations and parametric analyses are shown in figures 7 and 8. The parallel-burn vehicle (figure 7) uses four $\text{LO}_2/\text{RP-1}$ gas generator engines with four LO_2/LH_2 engines. Vacuum thrust levels are 1809 kN (407 klbf) and 2050 kN (461 klbf), respectively, for each RP-1 and LH_2 engine. Whereas the LH_2 and LO_2 tanks are in the body, the RP-1 is stored in the central wing. This RP-1 is pumped from the wing tank outlets to the lower engines. The OMS tanks are located above the wing box. The series-burn vehicle (figure 8) uses six staged-combustion engines; three are $\text{LO}_2/\text{RP-1}$ engines and three are dual-fuel engines. For this vehicle, RP-1 is stored both in the wing and in two body tanks nested aft of the LO_2 tanks. The structural arrangements and load paths are identical to those of the reference single-mode VTO vehicle. The wing splice (figure 9) is just outboard of the wing tank, providing for efficient assembly and leak tests of the tank section. The composite wing skin structure is bonded to titanium fittings at the wing splice sections.

Summary mass properties of the vehicles are given in table 2. Figure 10 illustrates the percentage weight reductions that result from application of dual-mode propulsion. Both advanced technology and normal technology growth are used as bases for comparison. The relative weight advantages of dual-mode are more when applied to the larger (normal technology growth) vehicles.

LIFE CYCLE COSTS

Approach

The life-cycle costs (LCC) were calculated using the same methods and basis as in reference 1, but with the addition of cost estimating relations (CER) for the dual-mode engines. The cost model has as a basis the work breakdown structures, system development, schedules, traffic models, and operations schedules consistent with SSTJ programs focused towards a 1995 IOC (initial operational capability).

The schedule permits a time span of up to 10 years for supporting research and technology (R&T) activities. The main engine DDT&E extends from 1983 through 1991, with manufacturing beginning in 1989. An engine delivery schedule is presented in table 3. Five vehicles are used in flight operations, with 1,710 flights scheduled over a 15-year period after IOC.

Costs based on these schedules are presented in fiscal year 1976 dollars and in dollars discounted at a 10% annual rate. The costs include a 10% fee, and assume cost per pound of propellants as \$1.00 for LH_2 , \$0.02 for LO_2 , and \$0.06 for RP-1.

Engine Cost Estimating Relations

The relative merits of dual-mode propulsion compared to single-mode (all LO_2/LH_2) requires a comparison of relative total program costs, including main engine costs. Definitive costs of the various dual-mode candidates have not been derived as yet. Nevertheless, for this study, CERs for the engine DDT&E and production phases were selected as functions of thrust level based on data from a 1971 engine cost study (NASA/OART working paper MA-71-3) as well as expert engineering judgement including consistency with the engine costs used in reference 1.

These engine CERs are functions of vacuum thrust, as illustrated in figure 11. The equations are as follows:

Cost estimating relation (\$Million*)

Engine type	DDT&E	Production
LO_2/LH_2	① = $1.3(50 + 1.405F^{0.422}) - 183.4$	③ = $1.3(350 + 0.475F^{0.7})N^{-0.074} \times 10^{-3} + 0.5$
$\text{LO}_2/\text{RP-1}$	② = $1.3(50 + 0.865F^{0.422}) - 83.4$	④ = $1.3(270 + 0.024F^{0.8})N^{-0.074} \times 10^{-3} + 2.5$
Dual-fuel	Ⓐ = $0.55 \times \textcircled{2}$	Ⓒ = $1.15 \times \textcircled{3}$
Dual-fuel	Ⓑ = $1.55 \times \textcircled{2}$	

where F is the vacuum thrust, and N is the number of engines per vehicle.

For the dual-fuel engine, two equations are used, representing lower and upper extremes. The CER A is based on the approach that an RP-1 engine is developed, then additional development is needed to add a capability for switching the fuel from RP-1 to LH_2 and to add an extendible (two-position) nozzle. The CER B is based on the extreme approach that the complexities of the dual-fuel engine require not only the addition of the LH_2 cycle and extendible nozzle, but also requires duplicate development, tests and evaluations of RP-1 components to achieve the high performance of the RP-1 cycle in the dual-fuel environment. Costs are shown in subsequent tables to show the cost spread from CER A to CER B.

Figure 11 shows a point representing the DDT&E costs currently quoted for the main engine now being developed for the Space Shuttle (SSME - Space Shuttle Main Engine, $F = 2090 \text{ kN}$, 470 klbf). A CER curve has been drawn through this point parallel to curve

1. The level of CER 1 was selected with considerations that a LO_2/LH_2 engine for SSTO would cost less to develop than the

SSME engine inasmuch as the SSTO hydrogen engine would be similar to the SSME in thrust level and design, and also would have the technology growth associated with normal research and SSME product improvements over the next 10 years. If the SSTO were to use hydrogen engines with thrust levels more than 20%, say, from SSME thrust levels, the advantages of the similarity to SSME could not be realized. The DDT&E costs then would more nearly be represented by the CER that passes through the SSME point. The CER for LO_2/LH_2 engines is therefore chosen, as shown in figure

11, with a discontinuity where the thrust is 20% from the SSME thrust. The incremental cost at the discontinuity is \$260 million. For the dual-fuel engines, also, where the hydrogen vacuum thrust deviates more than 20% from that of the SSME, an increment of \$185 million was added to CERs A and B. These incremental values were only applied in the cost analysis to select the numbers of engines for the series-burn and parallel-burn vehicles. If these increments were as small as 10% (\$40 million), the selected numbers would not change, demonstrating that the discontinuity assumed here is not affecting our general decisions and conclusions.

SSTO Program Costs

The life-cycle costs are summarized in table 4 for the single-mode and dual-mode vehicles. The spread in DDT&E costs relate to the two dual-fuel engine CERs described previously. The program costs are less for vehicles with dual-mode than with single-mode propulsion, with savings at least \$435 million up to \$812 million, with a maximum percentage savings of 8.4%. Total costs for the series-burn and parallel-burn vehicles are within 4.2%, indicating that the LCC is not a strong driver in selecting among these two modes.

Table 5 shows costs for selected items. The DDT&E costs for engines are about 12% of those for the vehicle and other support. Engine production and spares costs are about 13% more for parallel burn, whereas LH_2 costs are more than twice as much. Variations of cost with numbers of engines were calculated that indicated lowest LCCs when three RP-1 and three dual-fuel engines were used for the series vehicle, and four RP-1 and four LH_2 engines were used for the parallel vehicle.

Other perturbations on SSTO dual-mode design parameters and cost were studied. All perturbations showed cost variations of less than 6% from the LCCs for the reference vehicles.

ADVANCED TECHNOLOGY RESEARCH PROGRAMS

In reference 1, twelve major R&T programs were identified as having good potential cost and performance benefits for application to SSTO program requirements. These programs, identified by title in table 6, were described (ref. 1) together with associated estimates of R&T funding and scheduling. These advanced programs are considered to require accelerated funding above the normal funding now projected to be allocated in these area. In the context of this study, dual-mode propulsion requires accelerated R&T focusing, and is part of the main engine technology area (programs 6, 7, and 8 of table 6).

Accelerated dual-mode propulsion R&T activities are required to achieve the engine performance and weight goals of reference 2 and used in this report for vehicle design and technology assessments. Objectives of these R&T programs are summarized as follows.

Main Engine Injectors/Chambers/Nozzles

Objectives: Improve high-pressure $\text{LO}_2/\text{RP-1}$ engine technology through intensive research of candidate components that may comprise the thrust chamber assembly. For dual-fuel engines, additional effort is required to ensure performance and hardware configuration compatibility with both RP-1 and LH_2 fuel.

Main Engine Pumps

Objectives: Determine pump design characteristics to achieve high (approximately 27.6 MN/m^2 , 4000 psia) chamber pressures for LO_2 and RP-1 propellants. Goals include increasing efficiencies and life and reducing weight.

Main Engine Cooling

Objectives: Improve cooling techniques by performance improvement and weight reductions of chamber, nozzle, and turbine cooling components. With parallel burn, improved LH_2 cooling at high chamber pressures is required using the gas generator cycle for RP-1 engines. With series burn using dual-fuel engines, research for regenerative LO_2 cooling is required.

Estimated costs for dual-mode advanced technology programs are shown in table 7. The annual funding levels for these R&T costs are shown in figure 11 (fiscal year 1976 dollars). A substantial amount of this research needs to be completed by 1984 to provide the required R&T base for the DDT&E activities that are under way then.

MERIT ASSESSMENTS OF DUAL-MODE PROPULSION

Various figures of merit (FOM) have been defined to help assess the relative cost and performance benefits of technology for SSTO applications. Important comparative parameters include mass properties and costs (e.g., table 8), research costs (fig. 12), and LCC savings per R&T cost ($\Delta\$/\text{LCC}/\Delta\$/\text{R}$).

A set of FOMs is presented in table 9 for the dual-mode propulsion technology area, referenced to the extended performance, single-mode VTO vehicle. The estimated upper and lower limits of I_{sp} and engine weight, taken as 95% confidence limits, were applied to vehicle resizing and program recosting. These data then, together with maximum and minimum estimates of R&T costs, yield the maximum/minimum values of FOMs for comparison with the expected values. As discussed later, the dual-mode FOMs have values that show this technology area has good potential cost and performance benefits compared to many other technology areas listed in table 6.

Figure 13 shows the LCC savings as function of R&T cost for expected values as well as maximum and minimum values of the parameters. The percentage variations in R&T costs for dual-mode propulsion were assumed to be the same as for single-mode propulsion (ref. 1). The dashed line is reproduced from the results of reference 1, dividing the technology areas with FOMs in the upper quartiles from those in the lower quartiles. Data near this line, or above it, indicate good potential FOMs, as the dual-mode propulsion exhibits here. Data are also shown for the merit of dual-mode applied to vehicles with normal technology goals used in other than the dual-mode propulsion technology area.

Figure 14 shows the $\Delta\$LCC_D/\Delta\R_D FOM, the program cost savings per research cost required to meet the technology goals of dual-mode propulsion. Here, as in figure 13, the FOMs show significant potential benefits for dual-mode; these benefits are larger when dual-mode is applied to vehicles with other normal growth rather than advanced growth. Again, the relative merits of parallel burn and series burn are about the same, but are somewhat dependent on the CER (A or B) selected for the dual-fuel engine DDT&E.

These FOMs rank in the Quartiles I and II of reference 1, indicating that dual-mode propulsion has a potential high yield. It is exceeded in rank only by the technology areas entitled integration engineering, miscellaneous structures, and wing and vertical tail structures.

A tabulation of high yield and critical technology was presented in reference 1. This table is repeated here (table 10) but with the addition of dual-mode propulsion technology. This area is considered to be in the category of accelerated growth, as it requires additional focusing of activities and funding beyond normal expectations. It is a high yield area because the present study has shown significant cost and performance benefits can be achieved through application of dual-mode propulsion to SSTO vehicles.

CONCLUSIONS

A fundamental goal of this study of dual-mode propulsion was to identify its potential cost/performance benefits applied to future earth-orbit transportation systems with vertical takeoff and horizontal landings. These systems used completely reusable, single-stage-to-orbit (SSTO) vehicles and had mission requirements similar to Space Shuttle, which the SSTO would replace in 1995. Both parallel-burn and series-burn propulsion concepts using RP-1 and LH₂ fuels were analyzed, based on engine characteristics defined by another current NASA-sponsored study.

The benefits of dual-mode propulsion were identified by parametric analyses of its impacts on vehicle size and program costs, and by defining specific vehicle characteristics for near-optimum designs based on minimum weight and cost considerations. Figures of merit were used to assess the potential of the dual-mode propulsion concepts and their relations to single-mode systems.

The major results of the study are as follows:

(1) Single-stage-to-orbit concepts have exceptionally worthwhile cost/performance merits as advanced earth-orbital transportation systems;

(2) The application of dual-mode propulsion concepts can significantly enhance the cost/performance benefits;

(3) The amount of enhancement using dual-mode depends on the levels of technology in other important areas (such as material, structures, surface insulation, and LH_2 propulsion). The merit of dual-mode propulsion is larger when applied with "normal" technology projections;

(4) Merit indicators of parallel burn vehicle concepts compared with series burn concepts were within 5%, showing a dry weight and hydrogen cost advantage for series burn. The life-cycle cost and life-cycle cost savings per dollar of required research were about the same for both concepts. Within the guidelines and tolerances of this study, therefore, both show about the same merit and are beneficial compared to single-mode propulsion concepts;

(5) Areas of dual-mode propulsion technology that need to be pursued to realize the goals required for SSTO vehicles are as follows:

- a) High chamber pressure, high efficiency hydrocarbon engines;
- b) Pumps for all propellants to achieve pressure and performance goals;
- c) Cooling of chambers and nozzles with LO_2 and LH_2 in conjunction with radiation cooling techniques;
- d) Nozzle extension with or without engine shutdown;
- e) Dual-fuel engine switchover from hydrocarbon to hydrogen fuel, preferably without engine shutdown.

(These are in addition to those high-yield and critical technologies described in reference 1.)

(6) Inasmuch as dual-mode propulsion showed significant potential for cost savings, more near-term R&T effort is indicated to pursue better definitions of engine concepts, engine costs and dual-mode vehicle concepts;

(7) Reduction of operations costs is a major goal for cost-effective advanced transportation systems. Dual-mode propulsion studies should therefore include analysis of relative costs of launch operations with various types of engines;

(8) Other engine concepts and high density fuels for applications to advanced transportation systems continue to be offered for potential assessment studies. These include, for example, linear engines, new dual-fuel concepts, and synthetic and methane fuels. Integration engineering is highly recommended as a continuing, accelerated program to assure focusing of these and other R&T activities towards technology areas with best cost/performance benefits.

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TABLE 1.- ENGINE PERFORMANCE PARAMETERS

Propellant	Type	P_c , mN/m ² (psia)	C^* , m/sec (ft/sec)	ϵ	I_{sp} , vac (sec)
LO ₂ /RP-1 O/F = 2.9	Parallel or dual-fuel (staged combustion)	27.6 (4000)	1796 (5893)	40	351.0
				55	356.5
				125	369.1
				200	375.2
	Parallel (gas generator cycle)	29.3 (4250)	1796 (5893)	42.7	351.0
				58.4	356.5
				132.8	369.1
				212.5	375.2
LO ₂ /LH ₂ O/F = 7.0	Parallel	27.6 (4000)	2240 (7350)	40	439.0
				55	445.2
				160	463.3
				180	465.3
	Dual-fuel	20.7 (3000)	2231 (7320)	200	466.3
				40	433.2
				55	439.0
				160	456.8
				180	458.8
				200	460.5

TABLE 2.- MASS PROPERTIES OF ADVANCED VTO VEHICLES

Item	Single mode		Dual mode			
			Parallel burn		Series burn	
	kg	lbm	kg	lbm	kg	lbm
Dry weight	114 029	251 390	88 314	194 700	82 994	182 970
Landing weight						
Without payload	117 430	258 888	91 335	201 359	85 956	189 500
With payload	146 913	323 888	120 818	266 359	115 439	254 500
Ascent propellant	1 041 766	2 296 700	923 405	2 035 760	1 010 401	2 227 553
LH ₂	130 221	287 088	77 451	170 751	36 639	80 775
LO ₂	911 545	2 009 612	761 841	1 679 572	789 841	1 741 302
RP-1	0	0	84 113	185 437	183 921	405 476
GLOW	1 207 219	2 661 463	1 060 929	2 338 948	1 143 084	2 520 068

TABLE 3.- ENGINE DELIVERY SCHEDULE

	Series	Parallel
Basic requirements		
5 vehicles x number of engines per vehicle	30 engines	40 engines
Spare engines, 20%	6 engines	8 engines
Component spares, 20%	6 equivalent engines	8 equivalent engines
Major overhaul, 50%	15 equivalent engines	20 equivalent engines
Vehicle test articles		
1-1/2 equivalent vehicles + 30% spares	12 engines	15 engines
Total (engines and equivalent engines)	69	91

<u>Year</u>	<u>1989</u>	<u>1990</u>	<u>1991</u>	<u>1992</u>	<u>1993</u>	<u>1994</u>	<u>1995</u>	<u>1996</u>	<u>1997</u>	<u>1998</u>	<u>1999</u>
Series burn	4	8	8	8	8	8	8	8	5	4	0
Parallel burn	4	8	10	10	10	10	10	10	10	5	4

TABLE 4.- LIFE CYCLE COSTS

Cost Item	Single Mode		Series Burn		Parallel Burn	
	FY '76 \$M	Discounted \$M	FY '76 \$M	Discounted \$M	FY '76 \$M	Discounted \$M
DDT&E	5336	1588	5106 to 5367	1519 to 1597	5280	1569
Production	1125	227	941	189	988	200
Operations	3216	239	2818	211	2974	219
Total	9677	2054	8865 to 9126	1919 to 1997	9242	1988
First Article Cost	283	----	239	----	250	----

TABLE 5.- COST COMPARISON

Item	Series FY '76 \$M	Parallel FY '76 \$M
<u>DDT&E Costs</u>		
Engines	435 to 696	573
Vehicle and support	4671	4707
<u>Production Costs</u>		
Vehicle set of engines	34	39
<u>Operations Costs</u>		
LH ₂ costs	144	300
Engine spares	180	204
RP-1 costs	42	19

TABLE 6.- ADVANCED TECHNOLOGY PROGRAMS

<u>Materials, structures, and design optimization</u>	<u>Propulsion</u>
1. Thermal protection systems	6. Main engine injectors/chambers/nozzles
2. Propellant tanks	7. Main engine pumps
3. Wing and vertical tail structures	8. Main engine cooling
4. Thrust structures	9. OMS/RCS systems
5. Miscellaneous structures	10. Triple point propellants
 <u>Secondary technologies</u>	 <u>Design criteria</u>
11. Subsystems weight reduction	12. Integration engineering

TABLE 7.- R&T COSTS FOR FOCUS ON DUAL-MODE PROPULSION

	Parallel burn engines		Series burn engines	
	LO ₂ + RP-1	LO ₂ + LH ₂	LO ₂ + RP-1	Dual-fuel
Cooling	\$12.0M	\$7.8M	\$12.0M	\$ 7.8M
Pumps	\$14.0M	None (use SSME technology)	\$14.0M	\$ 5.0M
Injector/Chamber/Nozzles	\$20.0M	None	\$20.0M	\$ 5.0M
Fuel switchover	None	None	None	\$ 9.0M
Totals	\$46.0M	\$7.8M	\$46.0M	\$26.8M
	 \$53.8M		 \$72.8M	

TABLE 8.- COMPARISON OF VEHICLE CONCEPTS, WEIGHTS, AND COSTS

	Vehicle		
	Single mode	Dual mode	
		Series	Parallel
Dry weight			
kg	114 029	82 994	88 314
lb	251 390	182 970	194 700
GLOW			
kg	1 207 219	1 143 084	1 060 929
lb	2 661 463	2 520 068	2 338 948
Total program costs, dollars in billions			
Fiscal year 1976	9.67	8.87 to 9.13	9.24
Discounted 10%	2.05	1.92 to 2.00	1.99
Merit index*, dollars/kg (dollars/pound)			
Fiscal year 1976	63.8 (28.9)	55.9 (25.4)	59.0 (26.8)
Discounted 10%	4.7 (2.2)	4.2 (1.9)	4.3 (2.0)
*(operations costs)/(number of flights)(payload)			

TABLE 9.- FIGURES OF MERIT

Technology program	Technology values		$\Delta \$R_D$ max \$M min	ΔW_{dry} kg (lbm)	$\Delta GLOW$ kg (lbm)	$\Delta \$$ DBT&E _D \$M	$\Delta \$$ Prod _D \$M	$\Delta \$$ Ops _D \$M	$\Delta \$$ LCC _D max \$M min	$\Delta \$LCC_D - \R_D \$M	$\Delta \$LCC$ $\Delta \$R$	$\Delta \$LCC_D$ max $\Delta \$R_D$ min
	I_{sp} , sec W, kg (lbm)	$\pm$ Tolerance										
Dual-mode propulsion												
1. Parallel burn												
RP-1 engine, I_{sp}	356.5	$\pm$ 2%										
W	1145 (2524)	+ 20% - 5%										
LH ₂ engine, I_{sp}	466.5	+1.9% -1.1%	32.8 44.6 25.1	-25 537 (-56 300)	-146 057 (-322 000)	19	27	20	66 147 -32	33.2 122 -77	8.1	2.0 5.9 -1.3
W	3062 (6750)	+ 10% - 10%										
2. Series burn												
RP-1 engine, I_{sp}	356.5	$\pm$ 2%										
W	2024 (4463)	+ 20% - 5%				69	38	28	135 172 16	90.7 138 -44	11.2	3.0 5.1 0.5
Dual-fuel engine, I_{sp}	460.5	$\pm$ 1.1%	44.3 60.3 34.0	-30 858 (-68 030)	- 49 895 (-110 000)	to	to	to	to	to	to	to
W	3868 (8527)	+ 20% - 5%				-9*	38	28	57 119 -61	12.7 85 -121	7.6	1.3 3.5 -1.0

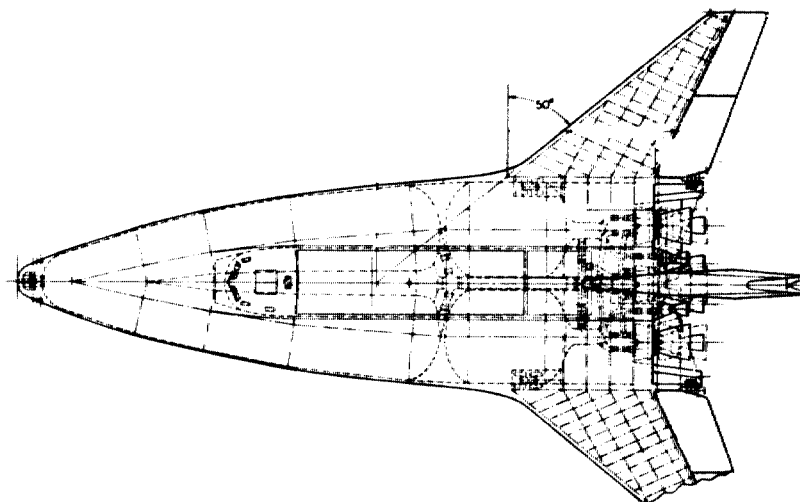
*Negative because of CER for engine uses 1.55 factor. Other negative values result from low projections of minimum engine performance.

The Δ s are relative to the extended performance single-mode VTO vehicle.

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TABLE 10.- HIGH YIELD AND CRITICAL TECHNOLOGY ASSESSMENTS

Technology area	"Normal" growth (focused)		Accelerated growth	
	High yield	Critical	High yield	Critical
1 Thermal protection systems Reusable surface insulation	X	X Reusability for more than 100 missions must be demonstrated	X	
2 Propellant tanks Dry wings Wet wings (applied to HTO)	X X	X Large wet wing cryogenic tank technology must be developed Lightweight pressurized structures Propellant utilization	X X	
3 Wing and vertical tail structures Composite materials	X		X	
4 Thrust Structures Composite materials	X		X	
5 Miscellaneous structures Composite materials	X		X	
6,7,8 Main engine propulsion Multiposition nozzles	X	X 2-position nozzle development is required Extension/retraction Nozzle cooling Seals Dynamic loads		
Dual-mode propulsion			X Parallel-burn concept: high performance LO ₂ /hydrocarbon engine required X Series-burn concept: high performance dual-fuel engine required	
9 RCS/OMS	Research not high yield nor critical			
10 Triple-point propellants	Not being vigorously pursued at present time		X	X (Based on timeliness) Technology for large scale applications must be developed Manufacture and storage
11 Subsystems weight reduction	X		X	
12 Integration engineering Design integration Design criteria	X	X Continued focusing of technology and evaluations of SSTD concepts are needed	X	
High yield: 1) Attractive cost/performance/benefits and/or dry weight improvements. 2) Technology not highly developed at present (1975-1976). Critical: 1) Technology development is necessary for SSTD cost and performance success. 2) Timely, near future, focus on SSTD-related research is recommended.				



Vehicle dry weight
 114 029 kg (251 390 lb)
 Gross Liftoff Weight
 1 207 219 kg (2 661 463 lb)

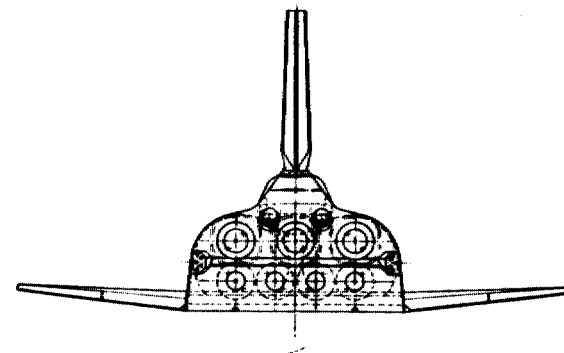
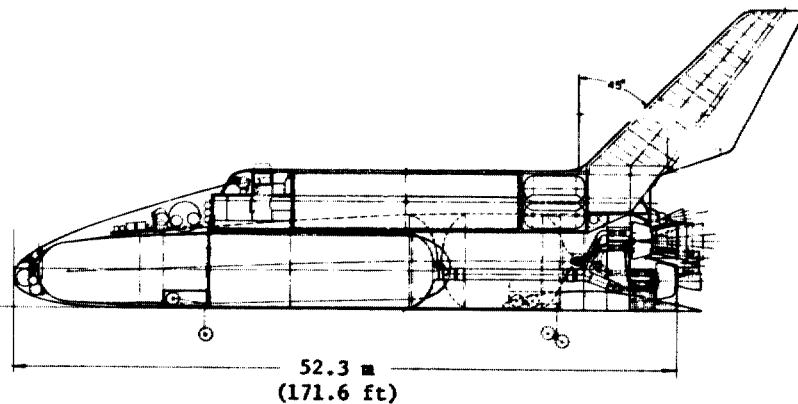


Figure 1.- Single-Mode VTO Vehicle

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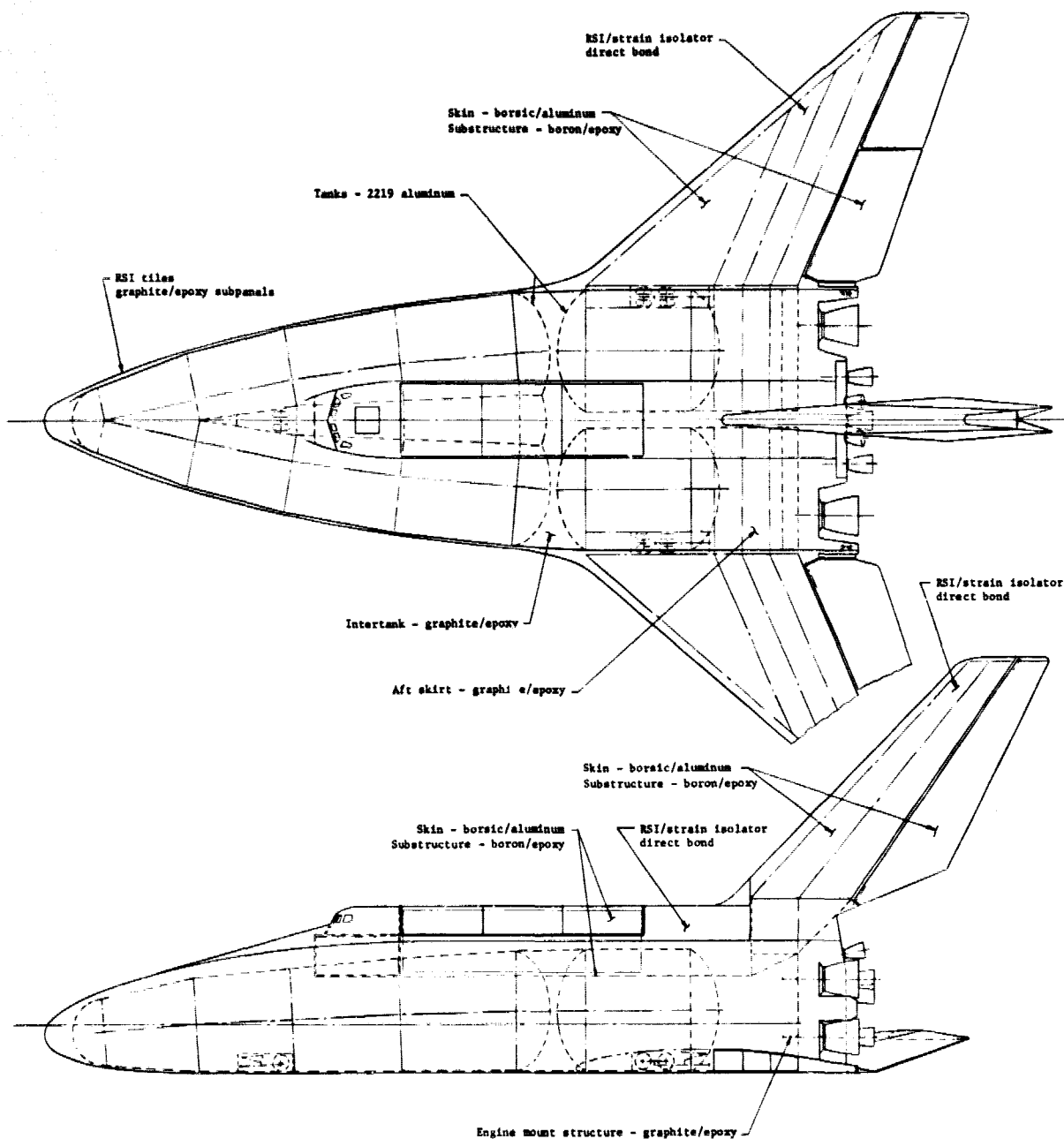
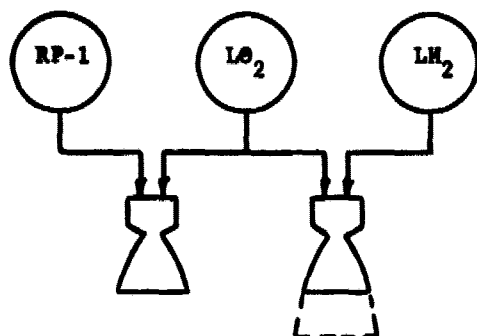
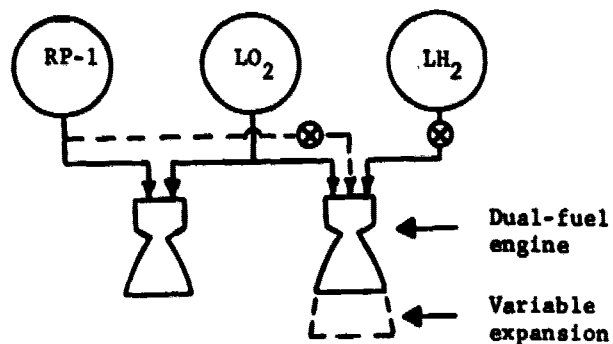


Figure 2.- Thermostructural materials.



$LO_2 + RP-1$ }
 $LO_2 + LH_2$ } Both at takeoff

(a) Parallel burn



$LO_2 + RP-1$ at takeoff
 $LO_2 + LH_2$ at altitude

(b) Series burn

Figure 3.- Dual-mode propulsion terminology

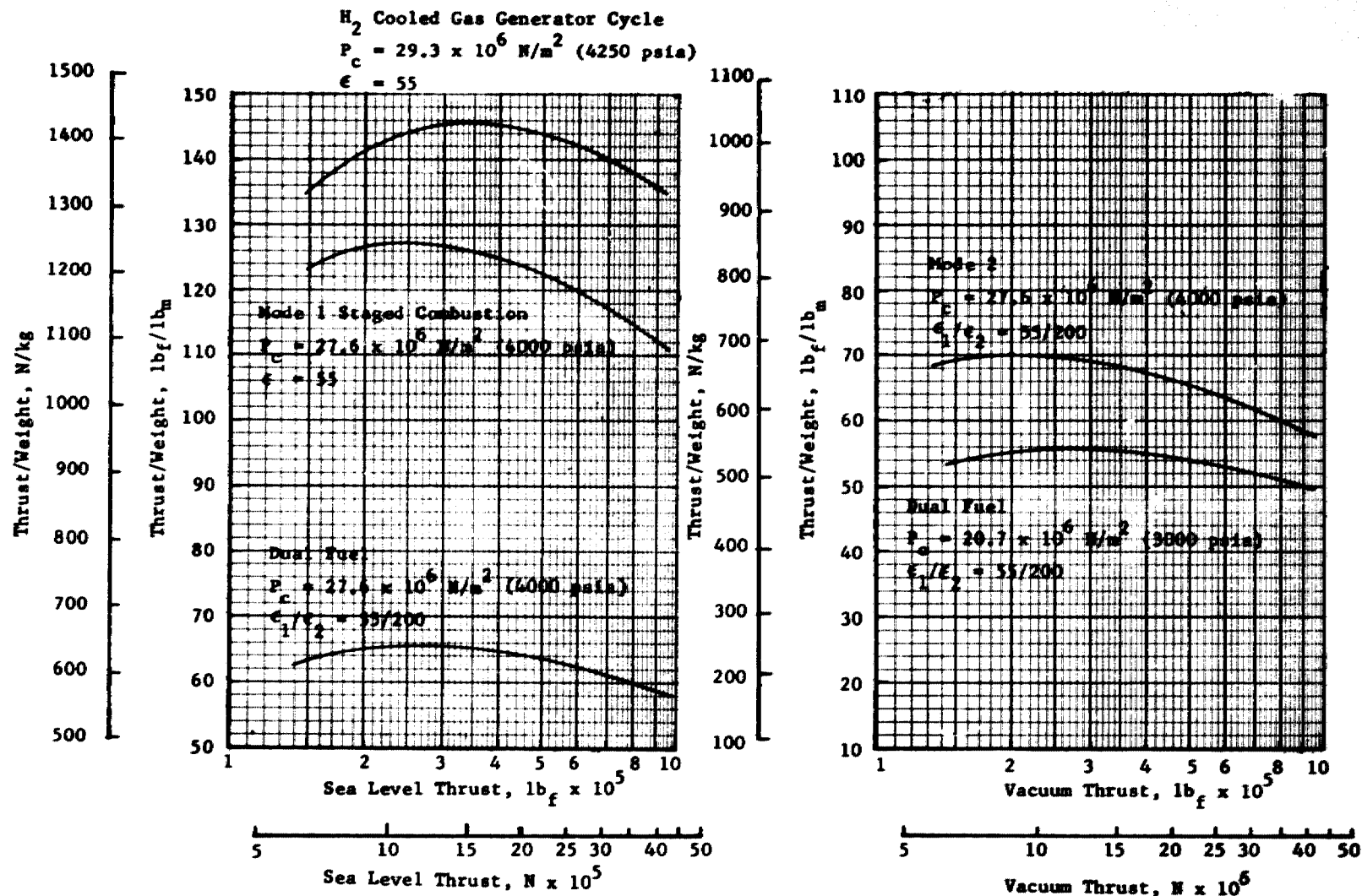


Figure 4.- Thrust/weight versus thrust

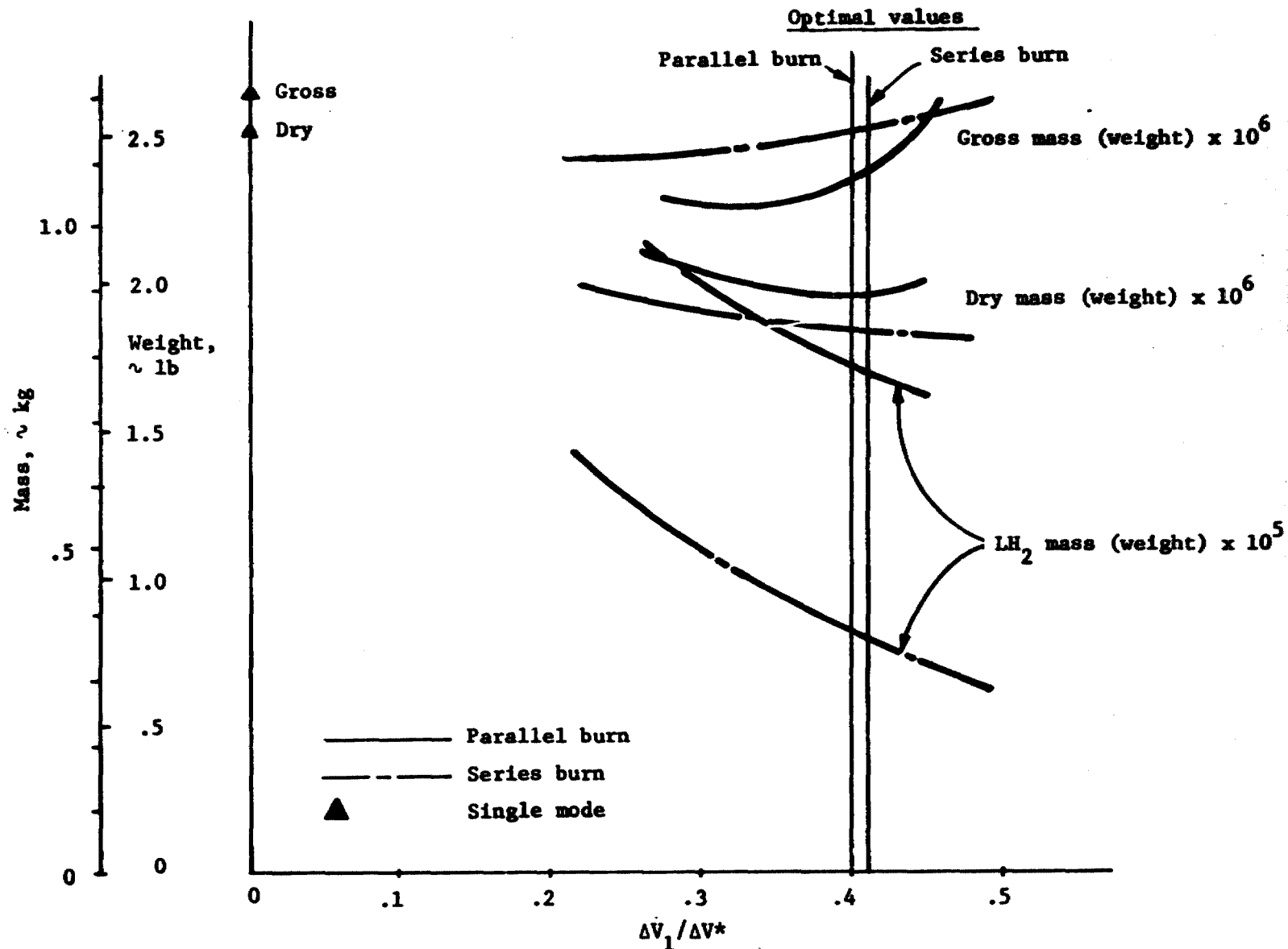


Figure 5.- Weight variation with ΔV_1

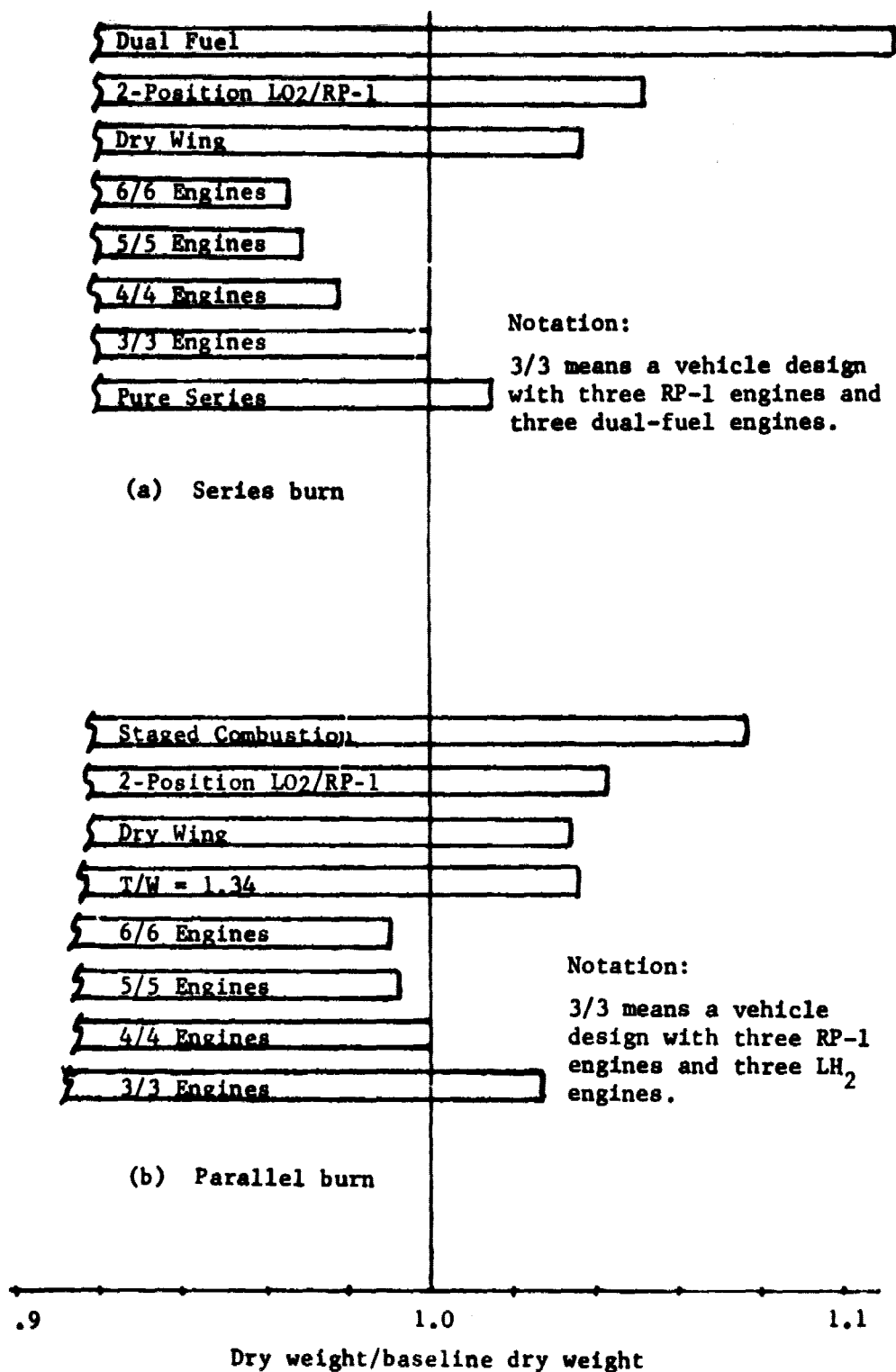


Figure 6.- Effects of design variations on dry weight.

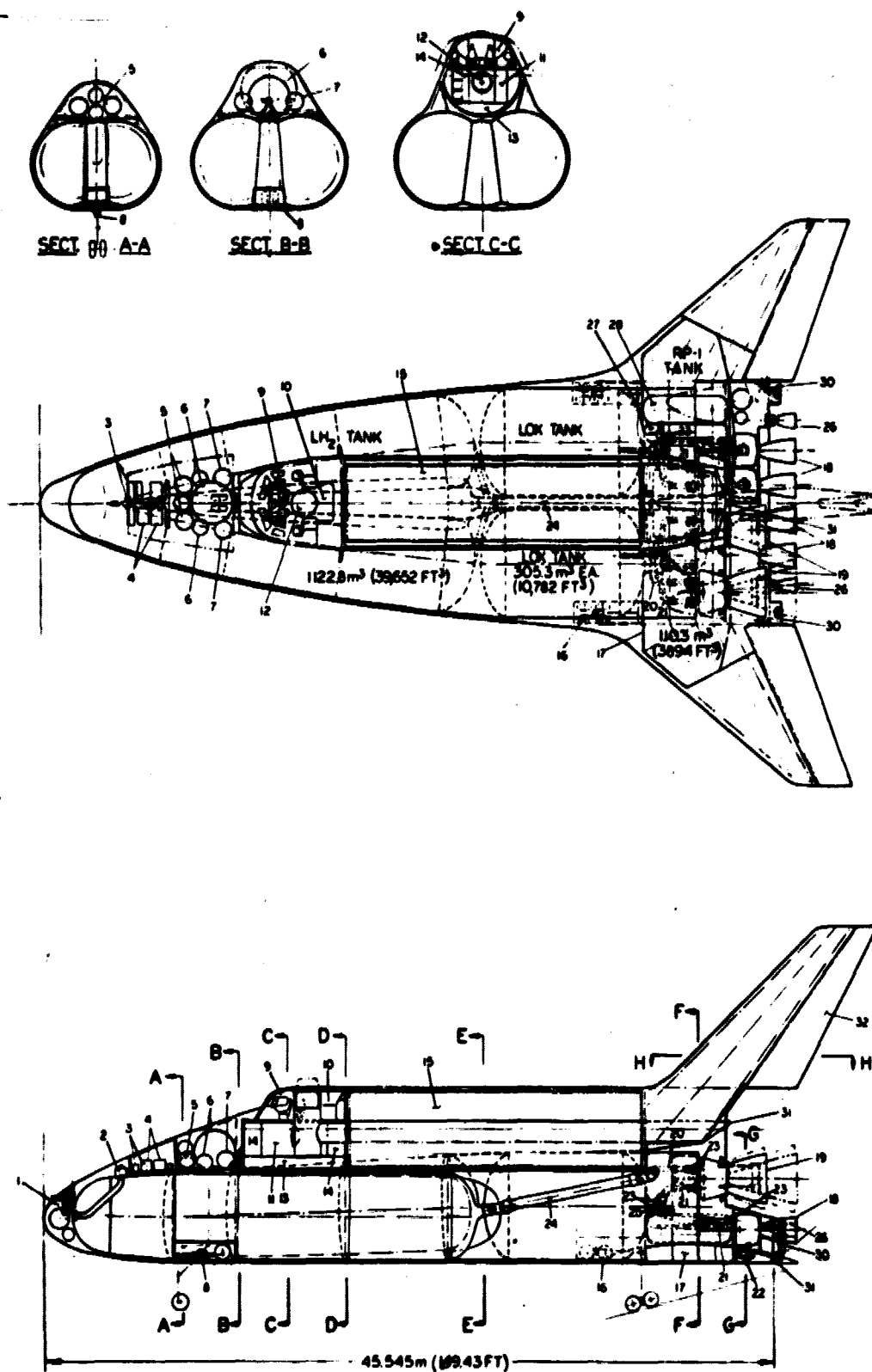
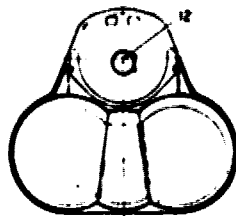
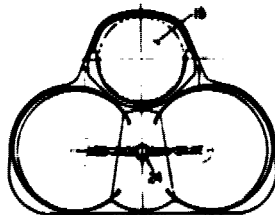


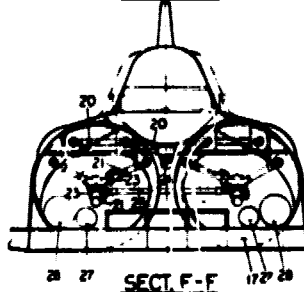
Figure 7.- Parallel burn vehicle, inboard



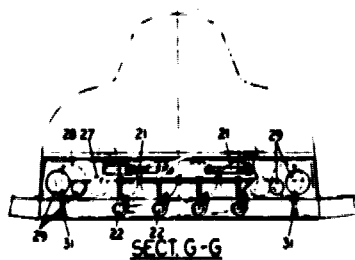
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SECT. E-E



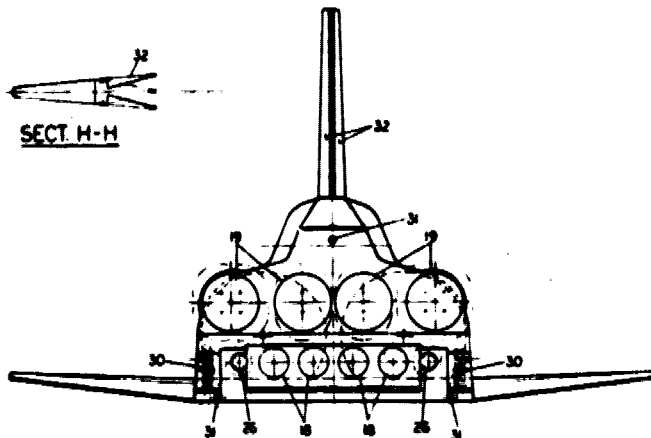
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SECT. G-G



SECT. H-H



SYMBOLS

1. FORWARD RCS MODULE
2. LM_2 TANK VENT AND PRESSURIZATION VALVES
3. ELECTRICAL POWER SYSTEM, FUEL CELLS
4. POWER SYSTEM, APU'S
5. FUEL CELL PROPELLANTS ($LOX-LM_2$)
6. APU PROPELLANT ($LOX-LM_2$)
7. PRESSURANTS (HE)
8. ROSE LANDING GEAR
9. FLIGHT DECK
10. OPERATIONS DECK
11. REST AND PASSENGER AREA
12. AIR-LOCK AND DOCKING MODULE
13. ECLSS - SYSTEM
14. AVIONICS
15. PAYLOAD BAY
16. MAIN LANDING GEAR
17. WING CARRY-THROUGH STRUCTURE/MP-1 INTEGRAL TANK
18. MAIN PROPULSION ENGINE, $LOX-AP-1$, $\theta = 55$, FIXED NOZZLE, NOT GIMBALLED
19. MAIN PROPULSION ENGINE, $LOX-LM_2$, $\theta = 55/200$, EXTENDABLE NOZZLE, GIMBALLED
20. LM_2 FEEDLINES
21. LOX FEEDLINES
22. MP-1 BOOST PUMPS
23. PROPELLANT PREVALUE
24. LM_2 MAIN FEEDLINE
25. LOX TANK INTERCONNECT LINE
26. GMS ENGINE, $LOX-LM_2$, $\theta = 400$
27. GMS PROPELLANT TANK, LOX
28. GMS PROPELLANT TANK, LM_2
29. RCS PROPELLANT TANKS, $LOX-LM_2$
30. AFT RCS MODULES
31. PAD SUPPORT HARD POINTS
32. SPLIT RUDDER

Figure 7.- Continued

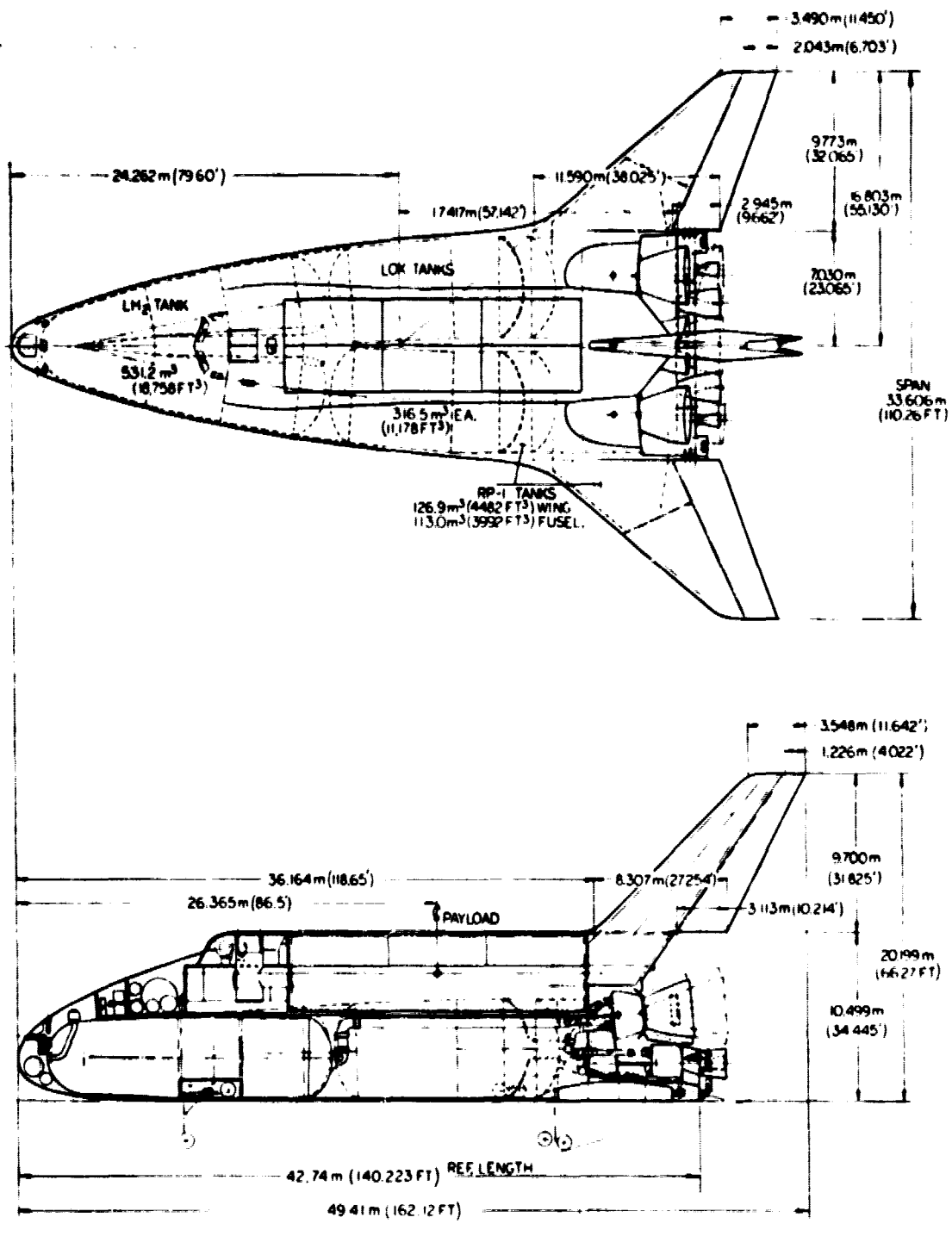


Figure 8.- Series burn vehicle, layout.

AREAS

BODY PLAN AREA	472.4 m ²	(5084 FT ²)
WING, THEORETICAL	351.3 m ²	(3781 FT ²)
WING, EXPOSED	147.4 m ²	(1586 FT ²)
ELEVON	48.8 m ²	(525 FT ²)
VERTICAL TAIL	57.5 m ²	(619 FT ²)
RUDDER	21.0 m ²	(226.5 FT ²)
BODY WETTED AREA	1,314.4 m ²	(14,148 FT ²)

VOLUMES

LH ₂ TANK	531.2 m ³	(18,758 FT ³)
LIX TANKS	633.0 m ³	(22,356 FT ³)
GP-1 TANKS	239.9 m ³	(8,474 FT ³)

PAYLOAD, DIAMETER	4.572 m	(15 FT)
PAYLOAD, LENGTH	8.268 m	(60 FT)

PAYLOAD BAY CLEAR OPENING

DIAMETER	4.725 m	(15.5 FT)
LENGTH	18.517 m	(60.75 FT)

WEIGHTS

			CG % REF LENGTH
PAYLOAD	29,863 kg	(66,000 lb)	61.69
DRY WEIGHT	82,934 kg	(182,970 lb)	
LANDING W/O PAYLOAD	85,096 kg	(189,500 lb)	68.00
LANDING WITH PAYLOAD	115,439 kg	(254,500 lb)	66.39
ASCENT PROPELLANT	1,010,401 kg	(2,227,555 lb)	
GROSS LIFT-OFF WEIGHT	1,435,003 kg	(3,150,068 lb)	65.45

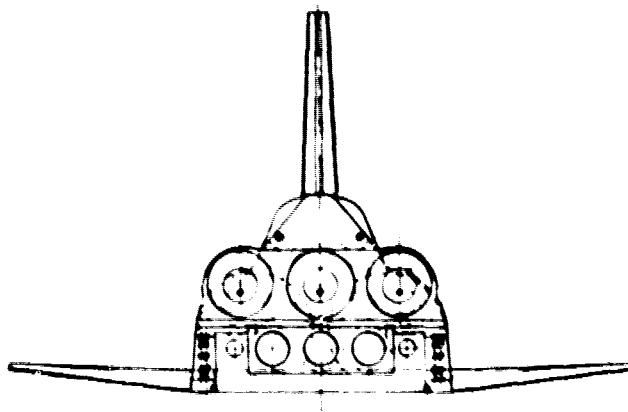
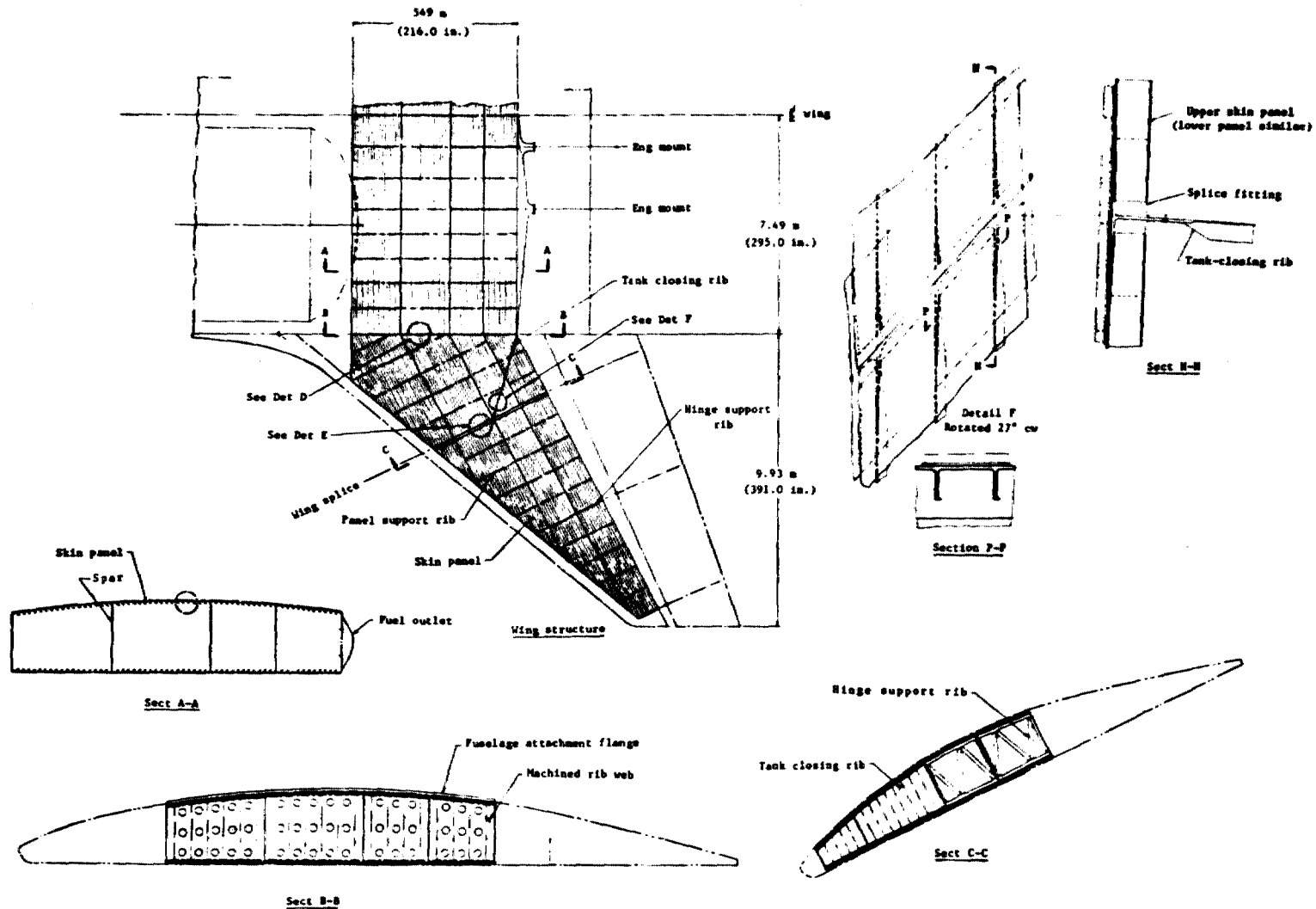


Figure 8.- Continued



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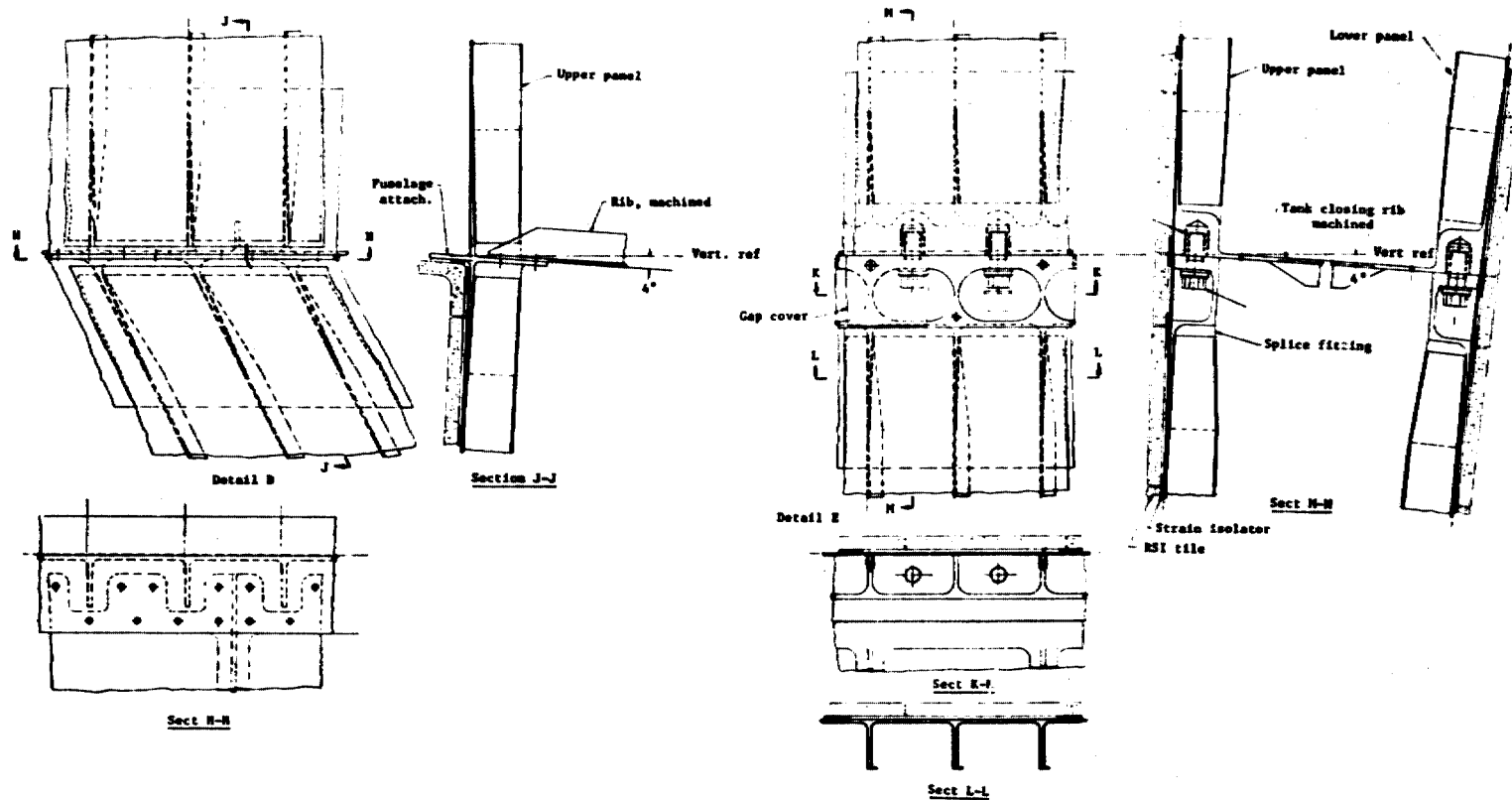


Figure 9.- Parallel burn vehicle, structures.

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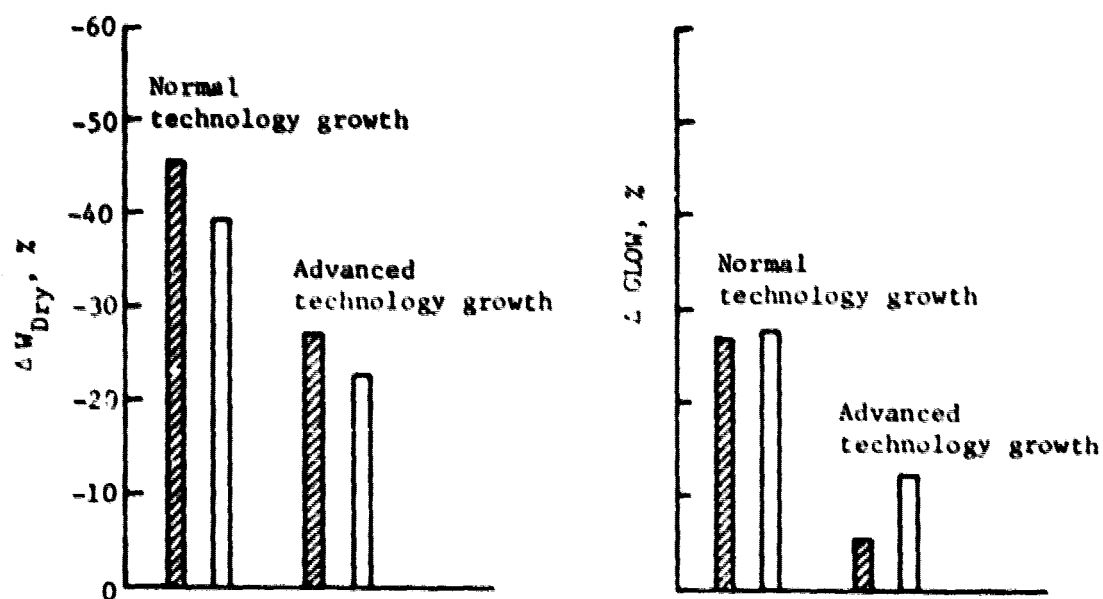
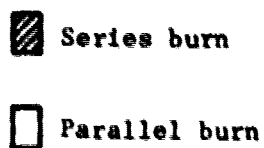


Figure 10.- Dual mode vehicle weight reductions relative to single mode VTO vehicles.

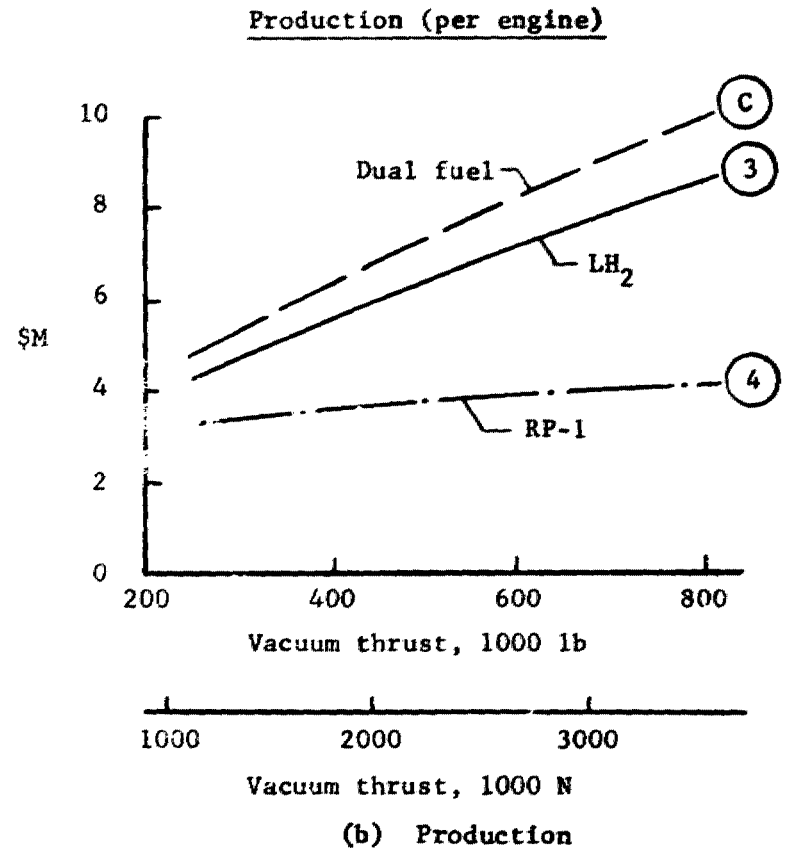
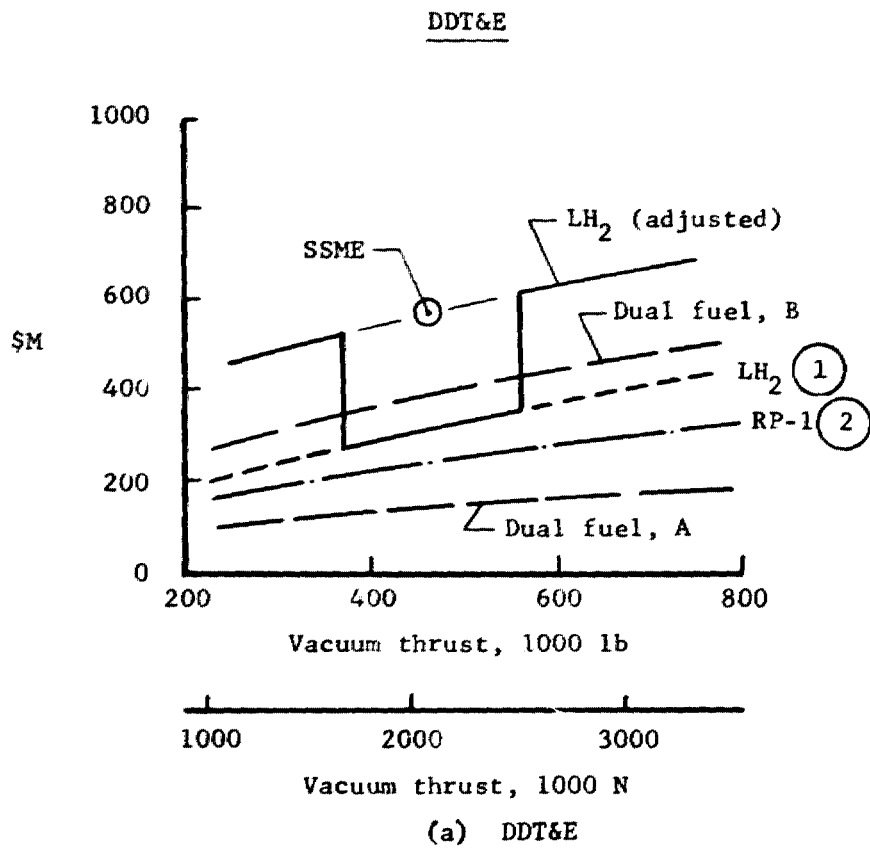


Figure 11.- Main engine costs.

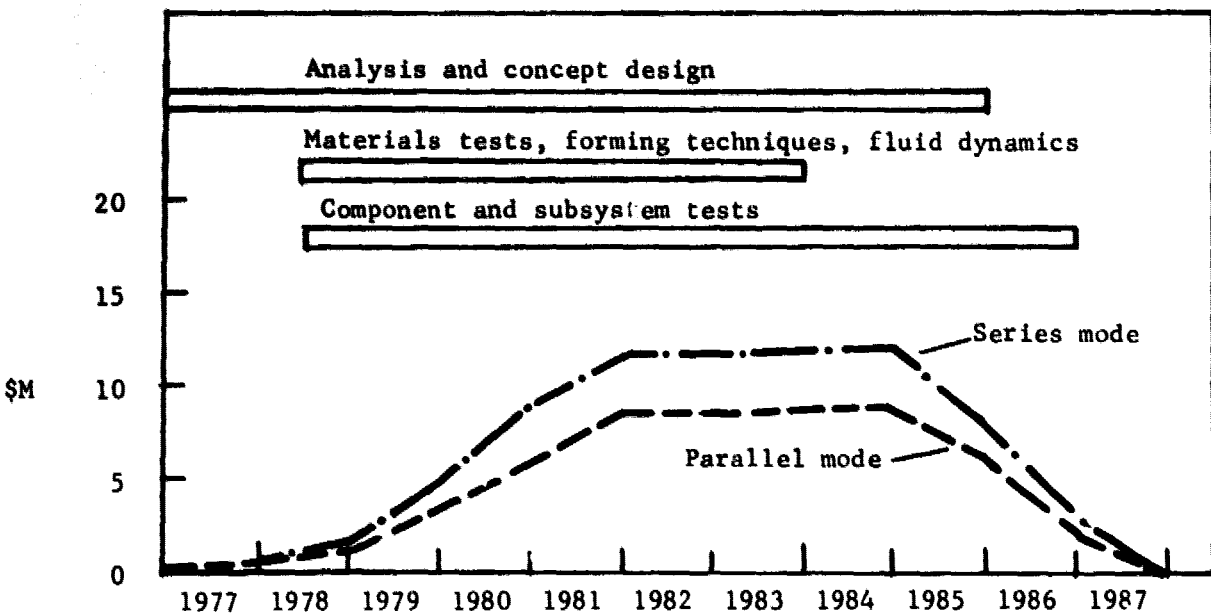


Figure 12.- Dual-mode propulsion R&T programs and cost.

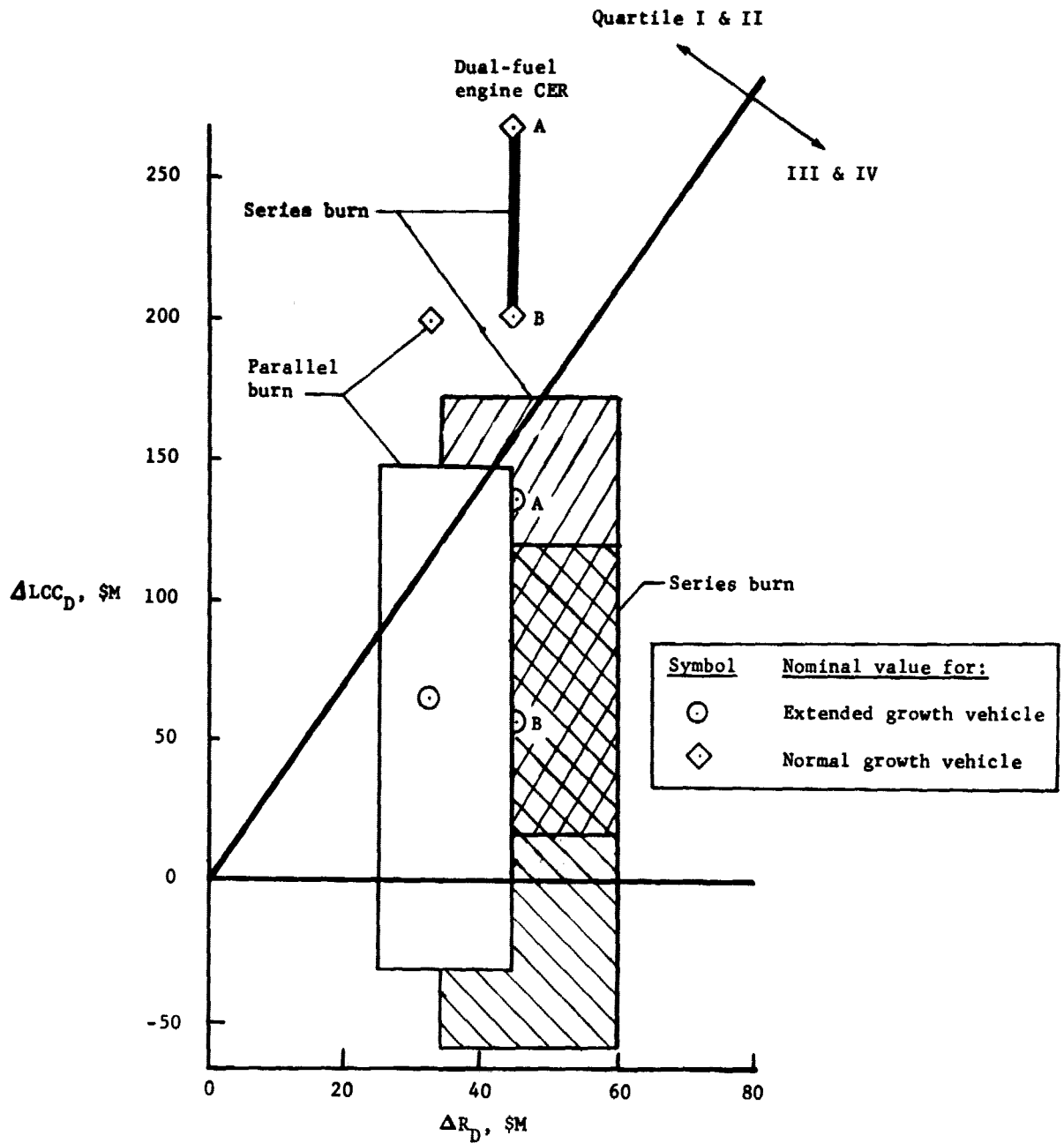


Figure 13.- Life-cycle cost figures of merit.

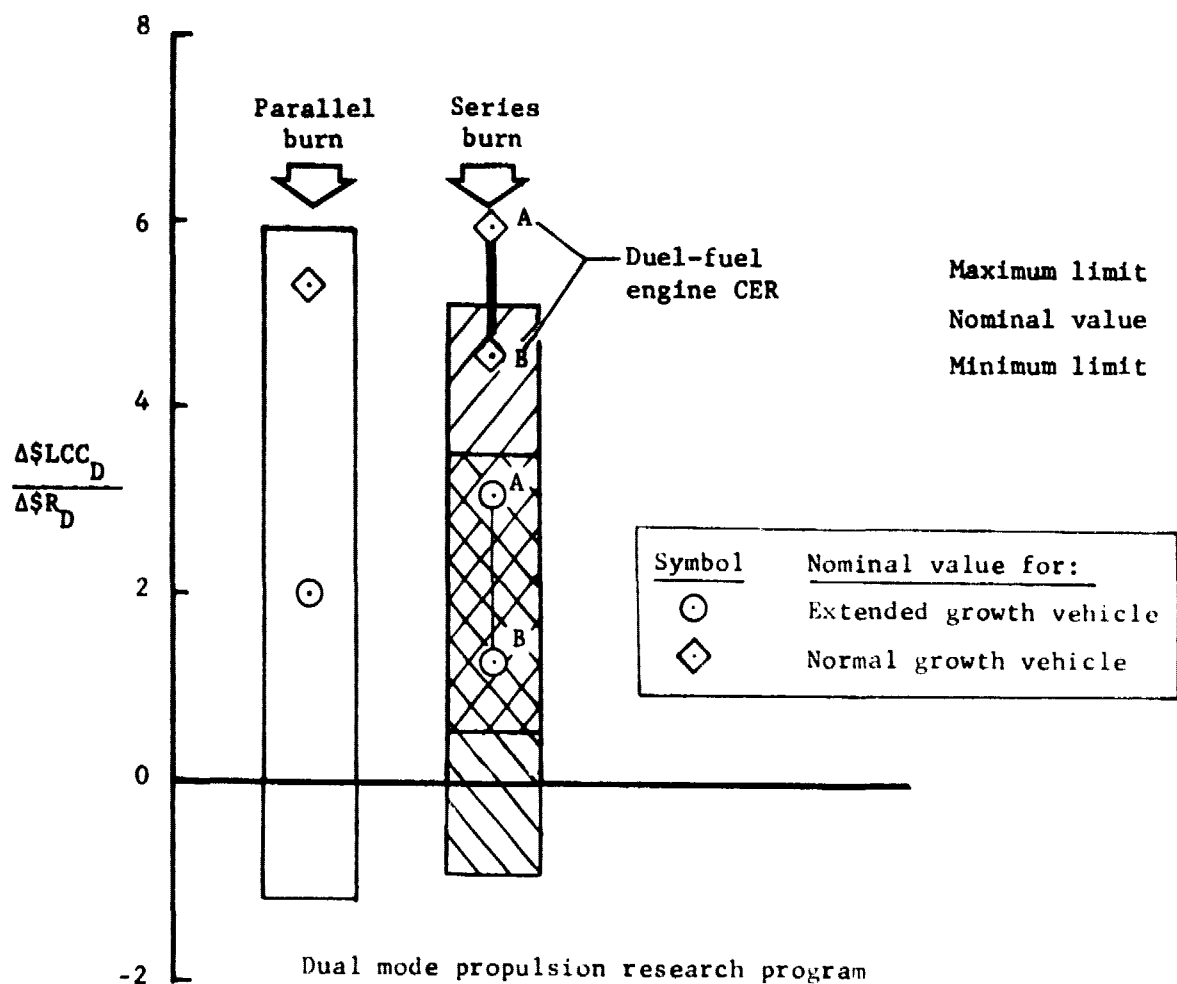


Figure 14.- Figures of merit comparison.